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EVALUATION OF A COMPARTMENTAL MODEL FOR PREDICTION OF NITRATE L--ETC(U)
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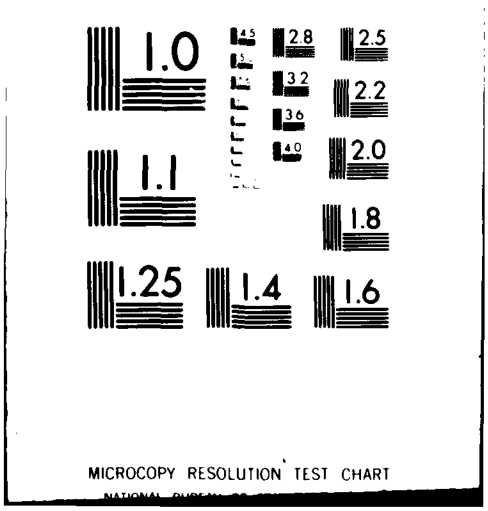
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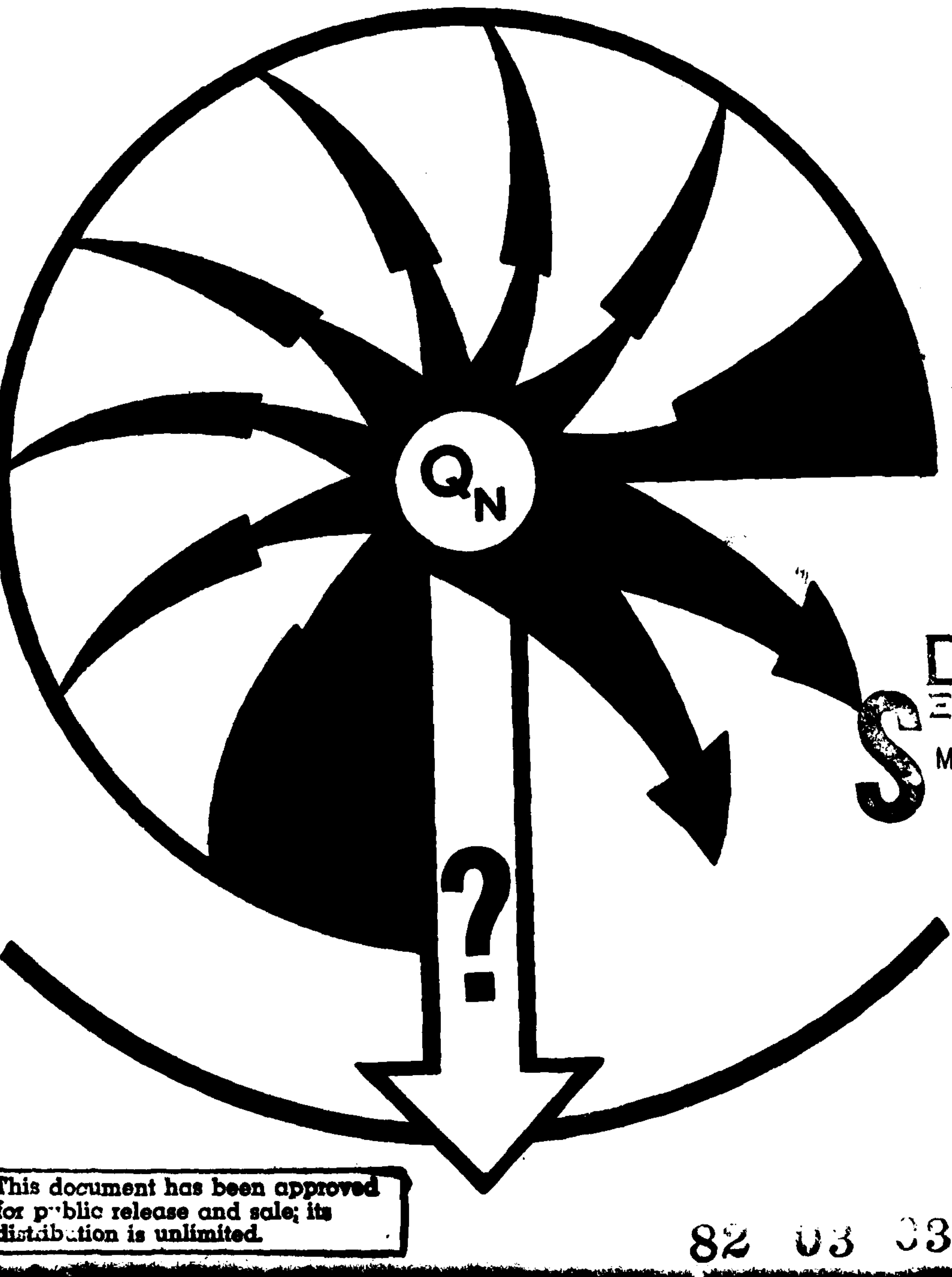
Evaluation of a compartmental model for prediction of nitrate leaching losses



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Cover: Symbolic representation of nitrogen input and output in land treatment of wastewater.

CRREL Report 81-23

Evaluation of a compartmental model for prediction of nitrate leaching losses

M. Mehran, K.K. Tanji and I.K. Iskandar

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A model is presented that consists of a water flow submodel and a nitrogen flow submodel. Irrigation, precipitation, evapotranspiration, surface return flow, and deep percolation are considered in the water flow submodel. The processes of nitrification, denitrification, mineralization, immobilization, plant uptake, and nitrogen fixation are included in the nitrogen flow submodel. The model has been applied to two sets of experimental data obtained from 1) controlled test cells at U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire, and 2) field plots of the University of California at Davis. Comparison between the experimental and model results indicates the potential capabilities of compartmental models in predicting nitrogen behavior in soil-water-plant systems under wastewater land treatment operations. This model is applicable to slow rate, rapid infiltration, and overland flow systems.

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PREFACE

This report was prepared by Drs. M. Mehran and K. Tanji of the Department of Land, Air, and Water Resources, University of California, Davis, and by Dr. I.K. Iskandar of the Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was conducted as a part of the U.S. Army Corps of Engineers Civil Works Project 31633, *Optimization of Automated Procedures for Planning, Design and Management of Land Treatment of Wastewater.*

The manuscript of this report was technically reviewed by Dr. H.M. Selim of Louisiana State University, Dr. D.R. Keeney, Department of Soil Science, University of Wisconsin, and Dr. D. Nielsen, Department of Land, Air and Water Resources, University of California, Davis. The authors appreciate the assistance of T.F. Jenkins in providing some data for model evaluation.

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ILLUSTRATIONS

TABLES

LIST OF SYMBOLS

a	runoff coefficient
b	fallow ET coefficient
C	denitrification coefficient
C_{iw}	N concentration in irrigation water
$C_{\ell\ell}$	concentration of N leaching losses
C_p	N concentration in precipitation
C_{sirf}	N concentration in surface irrigation return flow
d	gas loss coefficient for organic-N
D_{pet}	potential ET for grass in growing season
D'_{pet}	potential ET for grass in nongrowing season
e	corn ET coefficient
e_{iae}	irrigation application efficiency
E_{pan}	pan evaporation for growing season
E'_{pan}	pan evaporation for nongrowing season
f	deep percolation coefficient
g	gas loss factor for inorganic N
h	uptake coefficient
K	constant
K_{m1}, K_{m2}, K_{m3}	mineralization rate constant
ℓ	leaching fraction
L	length
m	mass
N_{aif}	applied inorganic N
N_{aof}	applied organic N
N_d	N mass denitrified
N_{dp}	N mass in deep percolation
N_{fn}	fixed N
N_{hc}	harvested uptake by plant
N_{hca}	adjusted harvested uptake by plant
N_{irz}	mineralized N input to root zone
N_{isn}	resident inorganic soil N
N_{iwronp}	mass of N pickup by irrigation water runoff
$N_{\ell\ell}$	mass of N leaching losses
NMCF	N mass conversion factor
N_{osn}	resident organic soil N
N_{pronp}	mass of N pickup by precipitation runoff
N_{risn}	residual inorganic soil N
N_{sirf}	N mass in surface irrigation return flow
Q_{dp}	deep percolation
Q_{et}	evapotranspiration
Q_{iw}	irrigation water
$Q_{\ell\ell}$	leaching loss
Q_p	precipitation
Q_{sirf}	surface irrigation return flow
Q_{sw}	soil water
R	potassium/nitrogen ratio
s	source or sink
t	time
x	applied N variable
x_m	minimum x
y	yield
y_{max}	maximum yield
z	distance

EVALUATION OF A COMPARTMENTAL MODEL FOR PREDICTION OF NITRATE LEACHING LOSSES

M. Mehran, K.K. Tanji and I.K. Iskandar

INTRODUCTION

Land treatment of municipal wastewater has gained much attention in recent years, primarily because of the scarcity of water in arid and semi-arid regions (Sanai and Shayegan 1978), the high energy cost of advanced wastewater treatment (Dryden and Chen 1978), the pollution of surface waters as a result of the direct discharge of sewage effluents, and the beneficial use of sewage constituents for agricultural production (Bouwer 1974, Kardos and Sopper 1974). Moreover, the provisions of sections 201(g)(5) and 313(b)(2) of the Clean Water Act of 1977 require that land treatment be fully studied as a feasible wastewater treatment alternative before the construction of any facility. Managing a land treatment system requires more than a thorough understanding of the nature of the effluents, soil conditions, and environmental factors. It also makes demands on the ability to predict and control the behavior of the overall system for optimal long-term operation.

Optimal operation could be achieved by resorting to experimentation. But this approach would not only be costly and time-consuming but might not provide the generalities we often need in extrapolating the results to new and different conditions. Modeling, on the other hand, is considered to be one of the most important tools for understanding, predicting, and controlling the behavior of nitrogen in natural systems, particularly those manipulated by man.

Realization of the objectives of the modeling effort is perhaps a key element in the initial formulation of a model. The existing knowledge of individual processes and mechanisms, as well as of the interrelationships among them and with the surroundings, form the foundation for potential conceptualization of the problem. Taking the process of modeling one step further, the degree of refinement or sophistication of the model depends on the modeler's ability to conceptualize and mathematically describe the events which are thought to be of prime importance in attaining the objectives in mind.

Modeling approaches

The concepts of systems analysis have provided the essential building blocks of most, if not all, modeling activities in many diverse disciplines and have helped bring an understanding of the behavior of systems under natural and artificial stresses (Endelman et al. 1972, Van Dyne 1970, Schultz 1969).

Various modeling approaches have been taken to describe the biophysical and chemical phenomena of land application of wastewater. They can be broadly classified as conceptual and dynamic. In this report we refer to conceptual (or compartmental) models as those that attempt to organize a complex system into subsystems, compartments, blocks, pools, or reservoirs, primarily in order to simplify different simultaneous processes and interactions which take place in the system. Each compartment describes part of the system and the overall system functions in terms of fluxes between the subsystems (Gordon 1969). Although the selection of compartments is to some extent arbitrary, it is important to draw clear boundaries in accordance with the significant physical phenomena governing the behavior of the system. The relative time scale and size of the compartments and fluxes are of primary and crucial importance in the formulation of a compartmental model. Compartmental models may not reveal all the cause-and-effect relationships in the system but they can serve as tools for predicting the impact of long-term management alternatives, which in turn can provide useful guidelines for decision-makers and managers.

Dynamic models are more mechanism-oriented. They offer more insight into the individual processes within the system as well as the interrelationships among different processes. Dynamic models attempt to describe the events as the best approximation to what occurs in nature in comparatively small temporal and spatial increments. However, their large input data requirements, the high cost of obtaining the input data, the high cost of computer runs, and the difficulties involved in verifying model results limit their utility.

Existing models

Compartmental models of nitrogen transformations have been applied on geographical scales ranging from the global level to small laboratory experimental columns. On a global scale, the emission of nitrous oxide into the atmosphere and its impact on the ozone content of the stratosphere (Crutzen 1972) has raised questions with regard to the extensive use of N fertilizers (Olson 1978). Several investigators have compiled quantitative estimates of various compartments and fluxes contributing to the global N cycle (Hutchinson 1954, Erickson 1959, Delwiche 1970). One of the most recent estimates of the global N cycle was given by Söderlund and Svensson (1976). It was concluded that the global N balance estimate is not accurate because of uncertainties in estimating over time the N content in terrestrial and aquatic reservoirs.

The intensive use of N fertilizers in irrigated agriculture has caused regional and local increases in the nitrate content of groundwaters to levels where they are hazardous for human consumption and other domestic purposes (Commoner 1970). An increase in NO_3^--N concentration in groundwater in the Upper Santa Ana Basin, California, led to a study in which N pools and fluxes were estimated in order to identify the sources and sinks so that recommendations and guidelines could be developed for controlling and preventing future problems in the area (Ayers and Branson 1973). Calculations of the mass balance of N applied to 356,000 acres of the basin floor showed that large amounts of N per year are potentially available for leaching, accumulation or uptake by plants in future years. This excessive nitrate loading was attributed largely to land disposal of animal manures, municipal sewage effluents, and N fertilizers.

Aldrich (1972), using another highly aggregated pool approach for the Upper Sangamon River Basin, Illinois, suggested that N fertilizer is a significant contributor to the nitrate found in surface waters. Miller and Smith (1976) followed the same procedure as that used in the Santa Ana Basin study and concluded that information on N inputs and outputs must be greatly improved for more accurate estimates of N pools and fluxes within the rather complex Southern San Joaquin Valley Basin. Some of the most important unknowns included denitrification, N in return flows, and geological formations of substrata (Miller and Wolfe 1978).

Tanji (1976) applied a compartmental hydrosalinity model to the Panoche Drainage District, California, and predicted the surface irrigation return flow to within ±17% of the monitored value for 1975. A further verification of model outputs was the agreement between the calculated total dissolved solids (TDS) of the soil solution (7146 mg L^{-1}) and the measured TDS of tile drainage effluent concentration (6710–8900 mg L^{-1}) from a 678-ha tile-drained farm. Another model by Duffy et al. (1975), designed to predict NO_3^- content in the tile effluent, predicted the tile flow and the height of the water table on a 62-ha tile-drained field.

Compartmental models have also been applied to describe the major changes in soil N as a result of incoming, outgoing, and internal processes in greenhouse experiments (Tyler and Broadbent 1958), lysimeters (Allison 1955, Owens 1960) and field experiments (Boawn et al. 1960). An extensive review of N mass balance studies in greenhouse experiments and lysimeters was made by Allison (1965).

Fried et al. (1976) introduced a long-term concept for evaluating leaching losses as a result of agricultural practices. It was based on the assumption that the amounts of N fertilizer added at the usual application rates in highly productive soils over 50 to 100 years are so large relative to the amounts of native soil N that in the long run the contribution of the original soil N to N in the drainage water can be neglected (Kohl et al. 1978). It was suggested that the soil system will reach a steady state in which the net contribution of the soil N will approach zero and input will equal output. This steady-state concept was then used to evaluate the efficiency of added N fertilizers and leaching losses.

Based on the above concept (Fried et al. 1976) and the principle of mass balance, a compartmental steady state model was formulated to estimate N emission from cropped land (Tanji et al. 1977). The main assumption was that the net change in storage of soil N is zero on an annual basis. The state variables in the model consisted of nitrogen and water. This model was applied to two sets of experimental field data for corn monoculture. The model was applied reasonably well to Davis, California, corn plots at the Kearney Field Station where the soil was coarse-textured and low in residual organic matter. In contrast, the model grossly underestimated N leaching losses in the Davis corn plots because both the contributions from mineralization of soil organic N and residual inorganic N were neglected in the model.

This steady-state model was later extended so that

it would be applicable to transient conditions, including considerations for initial inorganic soil N as well as soil organic N (Tanji et al. 1979). It was applied to three irrigation regimes and four fertilizer treatments. The agreement between calculated and measured values of plant uptake, residual inorganic N and average annual soil solution N concentrations was generally good. This model will be discussed in more detail later in this report.

UNDERLYING PRINCIPLES FOR COMPARTMENTAL MODELING

Definition of the boundaries of the system to be modeled is perhaps the first step in the formulation of a compartmental model (National Research Council 1978). This enables the modeler to locate the points of inflow to and outflow from the system. Identification of inflows and outflows, as well as flows interconnecting the compartments within the system, and the recognition of major sources and sinks are essential components of model development. To proceed with a quantitative analysis, we have to define the size of the compartments (subsystems), rates of fluxes across the compartment boundaries, and rates of source and sink processes contributing to the state variable or variables under consideration. From the known values of fluxes and compartments, an unknown flux or compartment value can be computed. Depending upon the nature of the input data, the frequency of monitored or measured values, and the rates of changes in the sources and sinks, an initial time increment must be selected which may be subject to change as the processes of model development, calibration, and verification proceed.

Mass balance

One of the most fundamental laws of transport phenomena is the law of conservation of mass. The concept of material balance is not only a necessary condition for formulation of compartmental models but for any model comprising transport and transformation processes. Even in the most sophisticated dynamic models, a test of the analytical or numerical schemes can be performed by mass balance, particularly in the case of nonlinear problems. Mass balance defines all inputs, outputs, and changes in storage of a material within a bounded region for a particular time interval. In one space dimension, this can be shown mathematically in the following manner:

$$\int_0^L m\,dx\Big|_0^t = \int_0^t m\,dt\Big|_0^L + \int_0^t \int_0^L s\,dx dt \qquad (1)$$

where m = mass

x = space coordinate

t = time

s = sources and/or sinks.

In eq 1, the term on the left-hand side represents changes in the storage from time 0 to time t for the entire domain. The first term on the right-hand side defines the net flow of mass in and out of the system with boundaries located at 0 and L while the second term accounts for all the sources and sinks contributing to a change in mass m within the bounded region during time interval t.

Steady state vs transient state

Compartmental models may describe systems having either steady or transient behavior. The assumption of steady state will reflect long-term trends and zero net change in storage. In systems where it is believed that a steady state prevails, the left-hand side of eq 1 approaches zero as the system moves toward a steady state. A true steady state, which is rare in nature, implies that the state variables are not changing with time. However, by selecting a proper time interval, pseudo-steady-state conditions may be treated as steady state (National Research Council 1978). Kohl et al. (1978) believed that it is advantageous to impose the steady-state assumption when the compartments are small compared to fluxes across them. One advantage of imposing a steady-state condition on the system is that it allows us to compute the unknown outgoing fluxes from the incoming fluxes by equating inputs to outputs. Models based on the steady-state assumption are generally in the form of a system of algebraic equations which could be solved either simultaneously or in sequences (Tanji et al. 1977).

Natural systems, particularly for the time intervals of usual interest, are under transient state conditions. This greatly complicates the formulation of the model because of the nature of flow rates, space and time dimensions, and functional relationships governing the transport and transformation mechanisms. For instance, in cases where the rate of change of a compartment is proportional to the size of the compartment, a system of simultaneous differential equations can be derived which, depending upon their complexity, can be solved analytically or numerically (Mehran and Tanji 1974, Van Dyne 1970). It should be pointed out that not all transient compartmental models are formulated in terms of differential equations and it is possible to have a system of algebraic equations describing the rate of change in state variables with time (Tanji et al. 1979).

Compartment size and level of aggregation

The most important consideration in setting up

compartments is selecting their size and the rates of fluxes across their boundaries so that they can be measured with a reasonable degree of accuracy (National Research Council 1978). This emphasizes the importance of proper selection of subsystem boundaries for each compartment. The degree or level of aggregation in a model depends primarily on the size of the system and the objectives of the modeling effort. Obviously, as the level of aggregation increases, the precision of the model outputs decreases. Models should, therefore, be structured to have small compartments relative to the fluxes across the boundaries so that the changes in the size of the compartments can be measured. This is particularly important where steady state conditions prevail, in which case the assumption of constant size of the compartment becomes experimentally difficult to verify. It is perhaps more reasonable in these cases to resort to an accurate measurement of fluxes rather than compartments (Kohl et al. 1978).

Most conceptual models which attempt to simulate the behavior of N in soil-water-plant systems are of the lumped-parameter type, meaning that input-output relations are examined only in terms of time and not in discrete spatial units. This implies that the state variable is averaged over the total space of any individual compartment or the system.

On the basis of available input data and existing data for validation, a choice must be made with regard to the type of model and its level of aggregation to provide the best methodology for evaluating the state variables at minimum cost. This emphasizes the importance of not only the cost of model development and validation, but also the cost of computer runs for new conditions. A sophisticated but inefficient computer model has limited utility.

CONCEPTUALIZATION OF N TRANSPORT AND TRANSFORMATION PROCESSES

The main objective of the compartmental model presented here is to compute the concentration and mass of nitrate leaching losses below the root zone. This general model is applicable to chemical fertilizer, municipal wastewater, and animal manure N inputs.

Since water is the primary carrier of mobile N species and a medium for almost all transformation mechanisms, a knowledge of the mass balance of water is essential in the computation for NO_3^--N concentration and mass. The model is composed of a water submodel and a N submodel and is derived from that of Tanji et al. (1979).

Water flow submodel

The processes contributing to losses and gains of water in the soil-water-plant system include irrigation, precipitation, evapotranspiration, surface return flow, and deep percolation. A schematic diagram of the fluxes and pools of the water flow submodel is shown in Figure 1. Knowing the amount of irrigation, precipitation, and evapotranspiration, the following relations define the unknowns in terms of known quantities:

$$Q_{sw} = e_{iae} Q_{iw} + (1-a) Q_p \tag{2}$$

$$Q_{\ell\ell} = Q_{sw} - Q_{et} \tag{3}$$

$$Q_{dp} = f Q_{\ell\ell} \tag{4}$$

$$Q_{dp} = f [e_{iae} Q_{iw} + (1-a) Q_p - Q_{et}] \tag{5}$$

$$Q_{sirf} = (1 - e_{iae} Q_{iw}) + a Q_p + (1-f) Q_{\ell\ell} \tag{6}$$

where Q_{sw} = soil water
e_{iae} = irrigation application efficiency
Q_{iw} = irrigation water
a = runoff coefficient
Q_p = precipitation
$Q_{\ell\ell}$ = leaching loss
Q_{et} = evapotranspiration
Q_{dp} = deep percolation

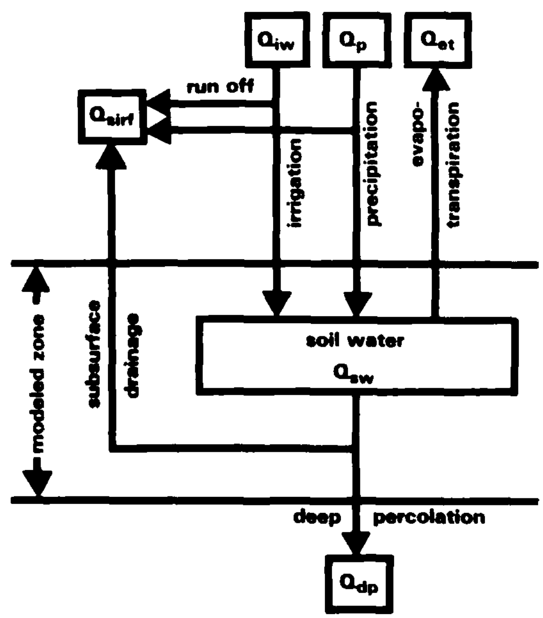

Figure 1. Schematic diagram of water flow submodel.

f = deep percolation coefficient
Q_{sirf} = surface irrigation return flow.

All water fluxes are in units of centimeters per year. Besides the known quantities mentioned above, three coefficients must be determined or estimated before the above equations can be solved, namely irrigation application efficiency e_{iae}, precipitation runoff coefficient a, and deep percolation coefficient f.

In the above formulation, it is assumed that the amount of evapotranspiration is measured or calculated so that leaching losses can be estimated. This is the usual case for almost all field conditions where leaching losses are estimated by difference. But in more controlled environments, such as those with lysimeters where drainage is measured, the above relationships will yield a value for Q_{et} by a simple mass balance for water.

Nitrogen flow submodel

The major pools and fluxes that are believed to contribute to N leaching or accumulation in the soil-water-plant system are shown in Figure 2. Applied N is composed of inorganic (N_{aif}) and organic (N_{aof}) fertilizers, N fixation (N_{fn}), and addition of N as a result of irrigation or wastewater (N_{iw}) and precipitation (N_p). Soil N consists of two measurable pools, namely the inorganic N and organic N pools, that may serve as sources, sinks, or both. The outputs of N include deep percolation (N_{dp}), plant uptake (N_{hc}), denitrification (N_d), and N in the surface return flow (N_{sirf}). All N fluxes are in units of kg ha^{-1} yr^{-1}.

The total input flux of N to the soil inorganic pool can be described by the following equation:

$$N_{irz} = N_{isn} + \mathrm{NMCF}[e_{iae} \cdot C_{iw} \cdot Q_{iw} + (1-a)C_p Q_p] + (1-g)N_{aif} + (1-d)(1-e^{-K_{m1}t})N_{aof} + (1-e^{-K_{m2}t})N_{fn} + (1-e^{-K_{m3}t})N_{osn} \quad (7)$$

where NMCF = N mass conversion factor
C_{iw} = N concentration in irrigation water
C_p = N concentration in precipitation
g = gas loss coefficient for applied inorganic N
d = gas loss coefficient for organic N
K_{m1}, K_{m2}, K_{m3} = mineralization rate constant
t = time.

The inorganic N pool (N_{irz}) is then subject to denitrification and uptake according to the following relations from which the amount of denitrified N (N_d) and the amount of plant uptake of N (N_{hc}) can be obtained:

$$N_d = C(N_{irz}) \quad (8)$$

and

$$N_{hc} = h(1-C)N_{irz} \quad (9)$$

where C is the denitrification coefficient and h the crop uptake coefficient. From the above relations, the amount of inorganic N subject to leaching can be computed as follows:

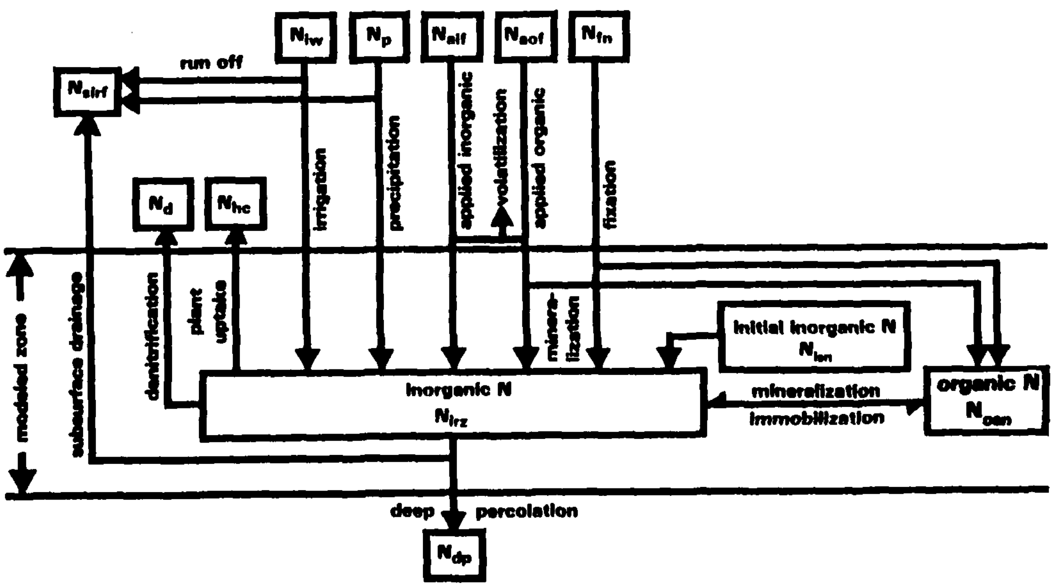

Figure 2. Schematic diagram of nitrogen flow submodel.

$$N_{\ell\ell} = \ell(N_{irz} - N_d - N_{hc}) \quad (10)$$

where ℓ is the leaching fraction defined as

$$\ell = \frac{Q_{\ell\ell}}{e_{iae}Q_{iw} + (1-a)Q_p} \quad (11)$$

and thus the concentration can be calculated as

$$C_{\ell\ell} = \frac{N_{\ell\ell}}{\mathrm{NMCF} \cdot Q_{\ell\ell}}. \quad (12)$$

In cases where intercepted subsurface drainage is zero, the mass of N in deep percolation N_{dp} will be equal to $N_{\ell\ell}$ as calculated from eq 10, but otherwise the following equation should be used:

$$N_{dp} = fN_{\ell\ell}. \quad (13)$$

The concentration and mass of N in surface return flow is calculated as

$$N_{sirf} = \mathrm{NMCF}\,[(1-e_{iae})C_{iw}Q_{iw} + aC_pQ_p + (1-f)C_{\ell\ell}Q_{\ell\ell}] + N_{iwronp} + N_{pronp} \quad (14)$$

where N_{iwronp} and N_{pronp} are the mass of N pickup by irrigation and precipitation runoffs, respectively, and

$$C_{sirf} = \frac{N_{sirf}}{\mathrm{NMCF} \cdot Q_{sirf}}. \quad (15)$$

Residual inorganic N_{risn} and organic N (N_{rosn}) at the end of time t are calculated as follows:

$$N_{risn} = (1-\ell)(N_{irz} - N_d - N_{hc}) \quad (16)$$

and

$$N_{rosn} = N_{osn}e^{-K_{m3}t} + (1-d)e^{-K_{m1}t} \cdot N_{aof} + N_{fn}e^{-K_{m2}t} \quad (17)$$

The parameters and coefficients used in the model will vary according to the particular conditions under study. The two case studies given in the next section will provide more insight into their nature, magnitude, and variation. Although Figure 2 shows that there are only two pools of soil N (N_{isn} and N_{osn}), it should be realized that they are in turn subdivided into smaller compartments for computational purposes. Therefore, the actual level of aggregation in the model is not as high as is indicated in Figure 2.

CASE STUDIES

The compartmental model described above was applied to two sets of experimental data obtained from 1) controlled test cells located at CRREL, and 2) field experimental plots at the University of California, Davis.

Case 1—CRREL test cells

In 1973 six outdoor cells were constructed of reinforced concrete with a square cross section, 8.5 m on each side and 1.5 m deep. Cells 1, 2 and 3 were filled with Windsor sandy loam soil and cells 4, 5 and 6 with Charlton silt loam. The average bulk densities of the two soils were 1.55 and 1.44 g cm^{-3}, respectively. Sewage effluent was obtained from a nearby housing community, given conventional primary or secondary treatment, disinfected with ozone, and applied by spray irrigation to the test cells. Cells 1 and 6 received 5 cm of secondary effluent per week during the growth season for five years. Other cells received varying amounts of either primary or secondary treated sewage effluents ranging from 5 to 15 cm throughout the 5-year period (Iskandar et al. 1976, Jenkins et al. 1978). Nitrogen applied to the test cells with treated wastewaters was primarily in the ammonium form. The average total N concentrations in the primary and secondary wastewater used were 26.0 and 26.9 mg N L^{-1}, respectively.

Required input data and coefficients

Total water inflow to the cells consisted of precipitation and applied sewage wastewater. Water percolating to the 1.5-m depth was collected and measured, allowing estimates for evapotranspiration by difference. Knowing the total amount of applied sewage and its concentration of N, total annual N input was calculated. Soil organic N (Table 1) was obtained from soil analysis data (Iskandar et al. 1979). The amount of N percolate for the period 1973-74 was estimated using available data on the amount of water applied and the percentage percolated for all cells from 1974 to 1978 (Fig. 3). The time increment used in the model was one year, beginning in June of each year. Initial organic N before the start of the experiment was assumed to be zero. The validity of this assumption will be discussed in the next section. Since there was no surface runoff in the cells, the application efficiency and deep percolation coefficients were considered to be unity while the precipitation runoff coefficient was taken to be zero. The concentration of N in precipitation was assumed to be 1.2 mg L^{-1}. The amounts of N fixation and net mineralization-immobilization were also assumed to be zero. This is because the amount of applied N is much greater than that produced by N fixation and experience has shown that, in slow rate systems, immobili-

Table 1. Summary of water and N input data for six test cells from 1973 to 1978 (Jenkins et al. 1981).

Period	Irrigation water (cm)	Precipitation (cm)	Percolation (cm)	Applied inorganic N (kg ha⁻¹)	Organic soil N (10³ kg ha⁻¹)
Cell 1					
1973-74	67	93	91*	353	44
74-75	149	74	148	673	62
75-76	92	116	135	324	59
76-77	93	99	123	399	71
77-78	67	86	113	348	71†
Cell 2					
1973-74	167	93	210*	928	41
74-75	451	74	447	2055	58
75-76	216	116	256	784	70
76-77	87	99	139	430	72
77-78	41	86	56	232	72†
Cell 3					
1973-74	70	93	96*	393	44
74-75	224	74	260	1072	72
75-76	92	116	141	361	63
76-77	85	99	132	429	77
77-78	41	87	57	233	77†
Cell 4					
1973-74	71	93	96*	393	87
74-75	216	74	248	1003	117
75-76	89	116	165	343	125
76-77	87	99	126	436	135
77-78	46	87	63	251	135†
Cell 5					
1973-74	141	93	183*	602	49
74-75	206	74	226	956	109
75-76	95	116	162	358	108
76-77	105	99	133	533	118
77-78	43	87	54	231	118†
Cell 6					
1973-74	67	93	91*	334	79
74-75	147	74	177	628	123
75-76	121	116	179	411	127
76-77	94	99	122	398	110
77-78	63	87	97	328	110†

* Estimated from Figure 3.
† Not measured in 1978; value of previous year was assumed.

zation equals mineralization over a short period of time (a few years).

The overall mass balance of N for all cells after five years showed approximately 5% of the N unaccounted for, and thus the denitrification coefficient for the model was assumed to be 0.05 (the denitrification also includes gaseous losses of N). Since there were no independent measured values for the rate of N uptake by grass, the annual uptake y was plotted against total applied N only for those cases which showed a recovery of applied N better than 85% (Fig. 4). For the above relationship, the following expression was used:

$$y = \frac{y_{max}(x - x_m)}{k + (x - x_m)} \tag{18}$$

where y_{max}, x_m, and k are constants with approximate values of 600, 150 and 400 respectively for the curve shown in Figure 4.

Using eq 18, the initial computations of the model resulted in higher annual uptake of N, particularly for the 1976-76 and 1976-77 periods, as compared with measured values. Because the experimental data showed that potassium (K^+) was deficient for forage growth during the above periods (Palazzo and Jenkins 1979), N uptake (N_{hca}) was adjusted according to the following empirical equation:

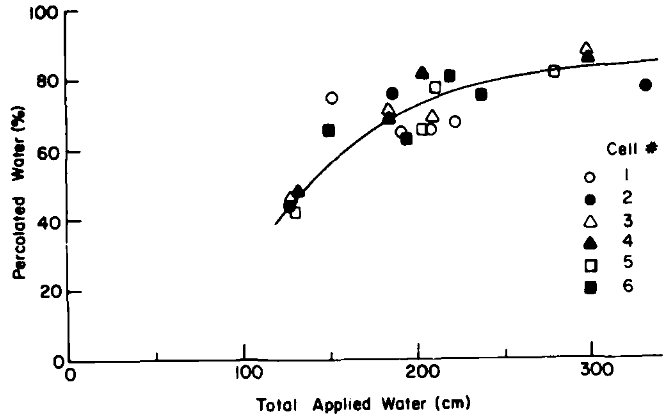

Figure 3. Percolated water (%) as a function of annual applied water for test cells 1 to 6 from 1974–1977.

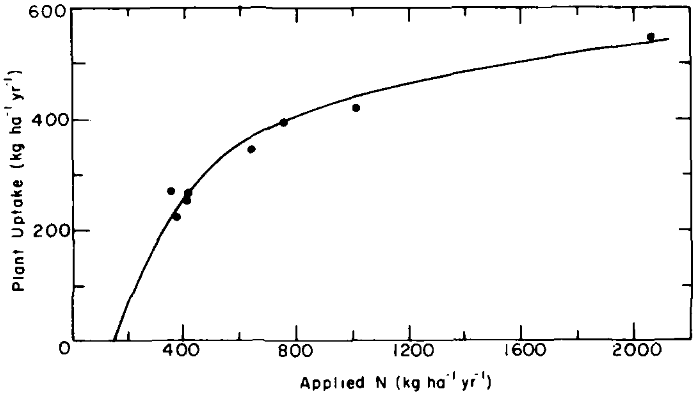

Figure 4. The relationship between applied inorganic N and plant uptake for treatments with less than 15% unaccounted N.

$$N_{hca} = N_{hc} - N_{hc}(0.9 - R) \tag{19}$$

where 0.9 is the optimum value of the ratio K/N (R) in the plants at which N uptake is neither suppressed nor enhanced by the amount of K (National Research Council 1970, Potash Institute of America 1973). Table 2 shows the ratio K/N in the plants, the exchangeable K in the soil (Iskandar et al. 1970, Palazzo and Jenkins 1979), and assumed values of R for the model. The increase in exchangeable K in the soil and K/N in the plants in 1977-78 shown in Table 2 was due to the application of 300 kg K ha^{-1} as KCl in May 1977.

Table 2. Measured K/N ratio, soil exchangeable K^+ and R values for the model.

Period	K/N in forage: Windsor	K/N in forage: Charlton	Exch K^+ in soil, meq (100 g^{-1}): Windsor	Exch K^+ in soil, meq (100 g^{-1}): Charlton	R
1973-74	0.83	0.83	0.12	0.09	0.9
74-75	0.83	0.73	0.14	0.22	0.9
75-76	0.78	0.70	0.06	0.07	0.6
76-77	0.72	0.80	0.07	–	0.6
77-78	1.13	1.58	0.35	0.44	0.9

A unique feature of the model application in this case study is that the model was run continuously from 1973 to 1977 for each cell; i.e. the residual inorganic soil N at the end of each year was used as the initial inorganic N for the subsequent year, except that the initial inorganic N was assumed to be zero for the first year.

Results and discussion

Figures 5-10 illustrate the results of the model as compared with measured values of plant uptake, mass of leaching losses, and average annual NO_3^--N concentration. Although a number of simplified assumptions were made in applying this model, the agreement between calculated and measured data is generally good, particularly with respect to plant uptake. The largest

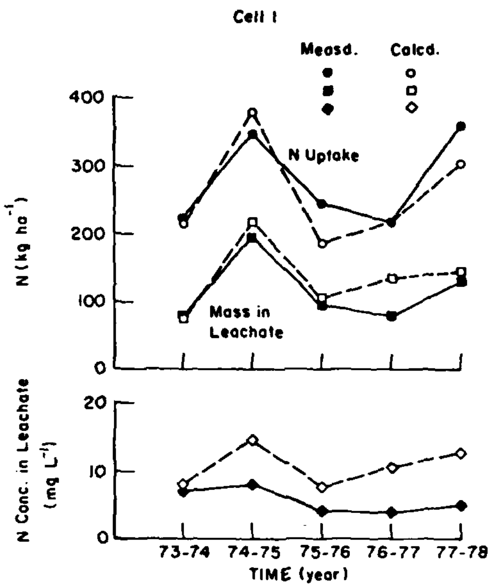

Figure 5. A comparison between measured and computed values of N uptake, and nitrate mass and concentration in the leachate in cell 1.

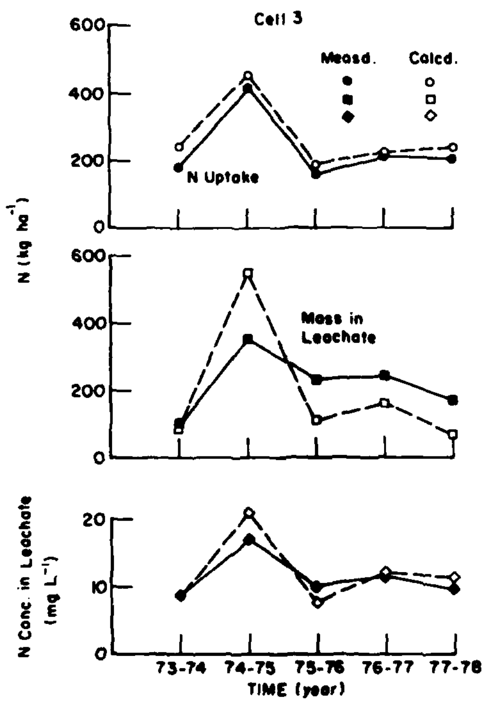

Figure 7. A comparison between measured and computed values of N uptake, and nitrate mass and concentration in the leachate in cell 3.

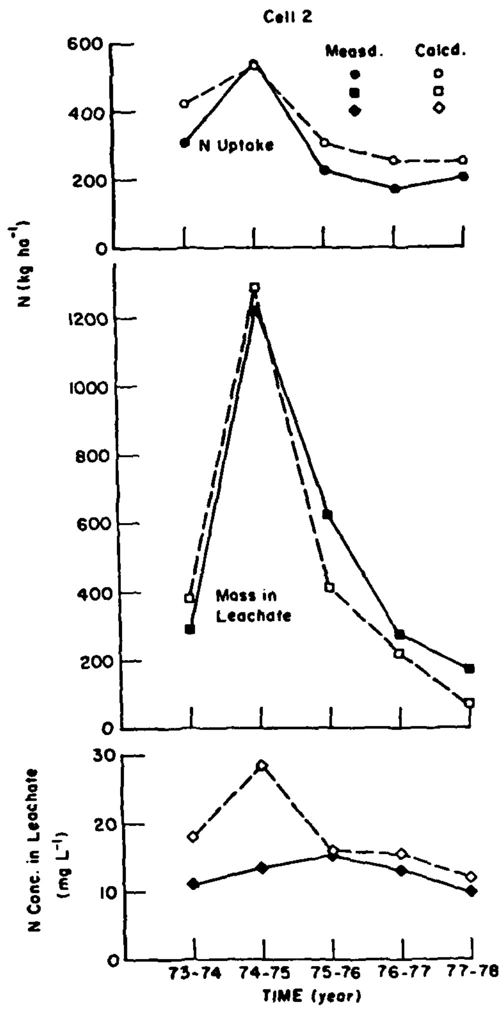

Figure 6. A comparison between measured and computed values of N uptake, and nitrate mass and concentration in the leachate in cell 2.

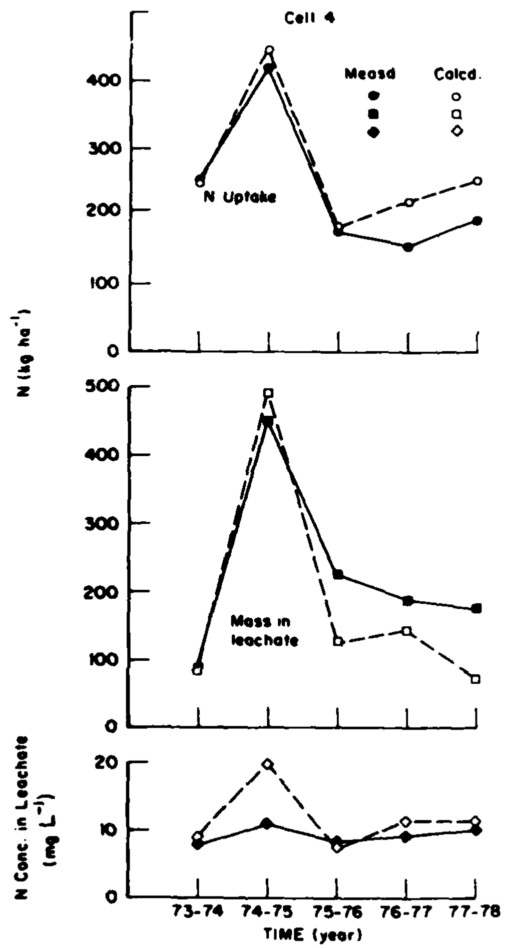

Figure 8. A comparison between measured and computed values of N uptake, and nitrate mass and concentration in the leachate in cell 4.

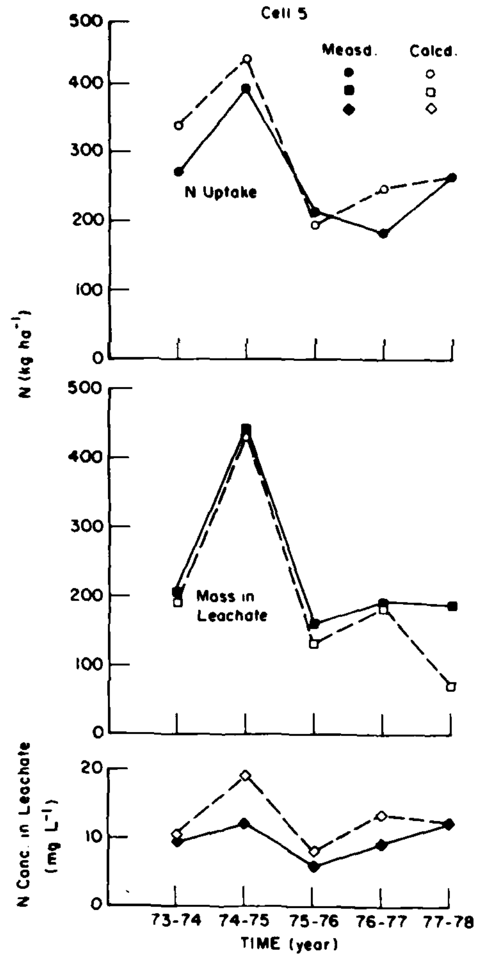

Figure 9. A comparison between measured and computed values of N uptake, and nitrate mass and concentration in the leachate in cell 5.

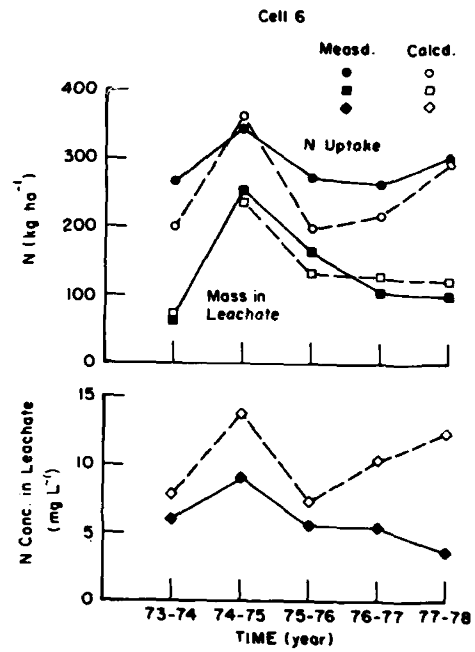

Figure 10. A comparison between measured and computed values of N uptake, and nitrate mass and concentration in the leachate in cell 6.

deviations occurred in concentrations of N in the leachate for 1974-75 and in the mass of N leaching losses for 1977-78. The best and the most consistent agreement was obtained in the case of cells 1 and 6. These cells received 5 cm per week of secondary sewage throughout the five-year period while the amount and type of effluent applied to the other cells varied each year, which could be a cause for some of the deviations between the measured and computed results. The good agreement in most cells between the computed and measured data for 1973-74 indicates that the assumption of 0 kg N ha^{-1} for initial organic N appears to be valid.

Considering the percentage of water percolated (Fig. 3) and the variations in N uptake with the amount of applied N (Fig. 4), it appears that the best use of N by grass is achieved where applied N and water do not exceed approximately **400 kg ha^{-1} yr^{-1}** and 170 cm yr^{-1} respectively. This equals approximately 5 cm per week of wastewater during a 4-month growing season (or application period) to either soil. This resulted in an annual average of less than 10 ppm NO_3-N. The same conclusion is arrived at by the model, indicating not only the importance of applied water and N in the effluent but also the amount of K^+ present in the soil. Reduction of the K/N ratio below 0.8 in the plants causes a drastic reduction in N uptake, resulting in an increase of available N for leaching. This is clearly shown in the measured leaching losses of 1975-76 and 1976-77 as well as in the model results.

Case 2—Davis field plots

As part of a University of California project entitled "Nitrate in Effluents from Irrigated Agriculture" supported by NSF-RANN,* a corn field trial was established in 1973 at the Davis campus of the University of California. Three irrigation regimes were used: 20, 60 or 100 cm of water was applied by sprinkler irrigation during the growing season (May through September), which corresponded to $^1/_3$, $^3/_3$ and $^5/_3$ respectively of the average corn evapotranspiration (ET) for the 1970-73 period (Biggar et al. 1974). All plots were pre-irrigated prior to planting so that the surface 3 m of the soil contained 100 cm of water. Fertilizer was applied at four rates: 0, 90, 180 and 360 kg N ha^{-1} of $(NH_4)_2SO_4$ at planting time at a 5-cm depth. The plots were instrumented with porous ceramic cups to extract soil solutions at depths of 0.3, 0.6, 1.2, 1.8, 2.4 and 3.0 m. After harvest, soil cores were taken at a 3-m depth to determine total inorganic and organic N present. The details of the experimental layout and procedures were reported by Biggar et al. (1974). This model was applied to two years of data, 1974-75 and 1975-76 (Tanji et al. 1979).

Required model input data and coefficients

Annual fluxes of water used as input to the model are summarized in Table 3.

The amounts of inorganic and organic N obtained in October of 1974 and 1975 after crop harvest are taken as initial values for the 1974-75 and 1975-76 periods. The data for all treatments are given in Table 4.

The coefficients required by the water submodel and the N submodel are given in Table 5. Since the water percolating past the 3-m depth was not directly measured as it was in the CRREL test cells, evapotranspiration loss Q_{et} was computed by

$$Q_{et} = e(D_{pet}) + b(D'_{pet}) \qquad (20)$$

where e and b are the corn and fallow ET coefficients, respectively. D_{pet} and D'_{pet} are potential ET for grass for the growing and nongrowing seasons, respectively, and are obtained from the following relations:

$$D_{pet} = K_p(E_{pan}) \qquad (21)$$

and

$$D'_{pet} = K_p(E'_{pan}) \qquad (22)$$

where K_p is potential ET coefficient for grass and E_{pan} and E'_{pan} are pan evaporations for the growing season and the fallow period, respectively. Rainfall data, pan evaporation data and ET coefficients were obtained from a nearby agroclimatic station and weighing lysimeter. Using eq 20, the annual amount of leaching past the 3-m soil depth was computed from eq 3.

The denitrification coefficient C was obtained by sensitivity analysis of the $^5/_3$ ET irrigation regime receiving 360 kg ha^{-1} of inorganic N (Tanji et al. 1979). The uptake coefficients, obtained by Broadbent (1976) from isotopically labeled N data, were 0.58, 0.56, and 0.39, respectively, for 90, 180 and 360 kg ha^{-1} of applied N. An extrapolated value of 0.6 for the uptake coefficient for the 0-kg N ha^{-1} treatment overestimated the amount of uptake (Tanji et al. 1979). By a trial and error method, it was found that a value of 0.35 for the uptake coefficient produced the best results. From the observed N deficiency of the corn in the 0-kg N ha^{-1} treatments, it appears that there is a threshold value of 10 mg L^{-1} NO_3^--N concentration in the soil solution below which the uptake efficiency decreases sharply.

* National Science Foundation-Research Applied to National Needs.

Table 3. Summary of water input data (cm of H_2O) for the three irrigation treatments in the 1975 (Oct 1974–Sept 1975) and 1976 (Oct 1975–Sept 1976) Davis corn plots.

Item	*1974–1975* $^1/_3$ *ET*	$^3/_3$ *ET*	$^5/_3$ *ET*	*1975–1976* $^1/_3$ *ET*	$^3/_3$ *ET*	$^5/_3$ *ET*
Irrigation water	18.9	59.3	100.7	20.2	60.5	102.7
Preirrigation*	17.2	5.4	6.2	40.5	28.3	5.9
Precipitation	46.5	46.5	46.5	17.5	17.5	17.5
Pan evaporation (growing season)	110.4	110.4	110.4	100.8	100.8	100.8
Pan evaporation (fallow period)	76.4	76.4	76.4	99.5	99.5	99.5

*Preirrigation prior to planting the 1976 corn crop was comparatively high due to a dry winter.

Table 4. Initial inorganic and organic soil N (kg ha^{-1} in 3-m profile) for four fertilizer and three irrigation treatments in the Davis corn field plots.
From analyses of soil N after harvest in October 1974 and October 1975.

Period	*Nitrogen applic. rate (kg ha^{-1})*	$^1/_3$ *ET* *Inorg. N*	*Org. N**	$^3/_3$ *ET* *Inorg. N*	*Org. N**	$^5/_3$ *ET* *Inorg. N*	*Org. N**
1974–1975	0	122	22,200	123	22,200	121	21,811
	89.6	132	22,200	104	22,200	119	22,200
	179.2	198	22,200	153	22,200	153	22,200
	358.4	364	22,200	331	22,182	342	21,711
1975–1976	0	110	21,947	120	21,936	117	22,454
	89.6	133	22,438	138	21,204	137	20,991
	179.2	184	22,251	139	21,052	134	21,824
	358.4	423	23,081	409	22,585	295	22,182

*Where organic soil N was not determined, an average value of 22,200 kg N ha^{-1} was assumed.

Table 5. Required input parameters and coefficients for the water and the N submodels.

Item	*Symbol*	*Value*
Irrigation application efficiency	e_{iae}	1.0
Precipitation runoff coefficient	a	0.2
Potential ET coefficient for grass	K_p	0.76
Corn ET coefficient	e	0.82
Fallow soil ET coefficient	b	0.52
Deep percolation coefficient	f	1.0
N concentration in irrigation water (mg L^{-1})	C_{iw}	0.2
N concentration in rainwater (mg L^{-1})	C_p	1.2
Gas loss coefficient for inorganic N	g	0.0
Gas loss coefficient for organic N	d	0.0
Mineralization rate for organic N (week^{-1})	K_{m1}, K_{m2}, K_{m3}	10^{-4}
Denitrification coefficient	C	0.15

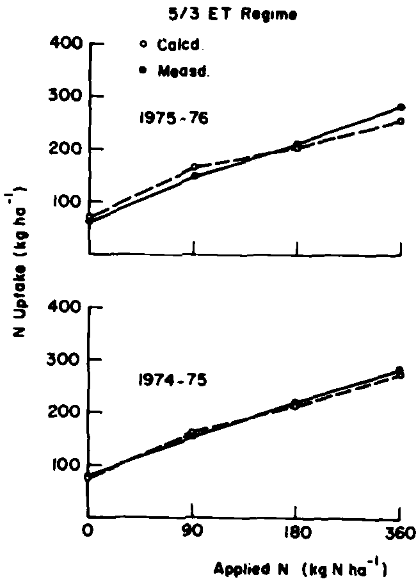

Figure 11. A comparison between measured and computed values of N uptake as a function of applied N for the $^5/_3$ ET treatment.

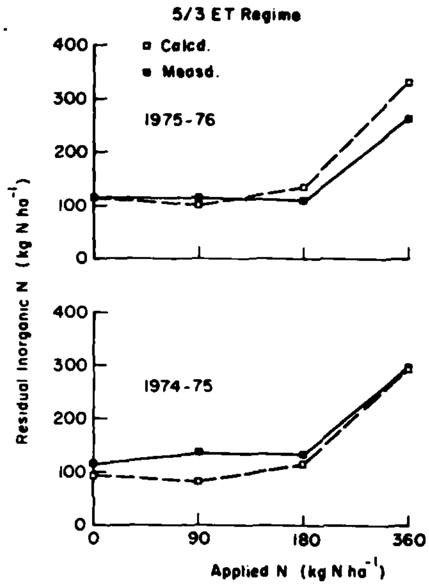

Figure 12. A comparison between measured and computed values of residual inorganic N as a function of applied N for the $^5/_3$ treatment.

Results and discussion

Figures 11–19 show the comparison between the measured and calculated data for N uptake, residual inorganic soil N and average annual N concentration in the soil solution at the 3-m depth for the $^5/_3$, $^3/_3$ and $^1/_3$ ET treatments of 1974-75 and 1975-76. The generally good agreement between the measured and calculated data indicates that the assumed values of denitrification and mineralization are reasonable for the soil and environmental conditions in the Davis plots.

Table 6 gives mass emission of N leaching losses past the 3-m depth for the $^3/_3$ and $^5/_3$ treatments. Zero N emission is calculated for the $^1/_3$ ET treatments because there was no downward flow of water at the 3-m depth due to the evapotranspiration losses exceeding the effective water input at the soil surface.

Table 6. Computed mass emissions of N (kg N ha^{-1} yr^{-1}) below the root zone (3 m) for the 1974-1975 and 1975-1976 corn field trials at the Davis site.

Ammonium sulfate fertilizer rate (kg ha^{-1})	*1974-1975**			*1975-1976**		
	$^5/_3$ ET	*$^3/_3$ ET*	*$^1/_3$ ET†*	*$^5/_3$ ET*	*$^3/_3$ ET*	*$^1/_3$ ET†*
0	28.0	2.4	0	13.2	0.52	0
89.6	37.0	3.2	0	20.2	0.78	0
179.2	53.1	4.8	0	26.8	1.03	0
358.4	133.4	12.0	0	66.7	2.95	0

*$^5/_3$ ET, $^3/_3$ ET, and $^1/_3$ ET are, respectively, 100-, 60-, and 20-cm irrigations during the growing season.
†N was not leached past the 3-m depth because of upward flow of water.

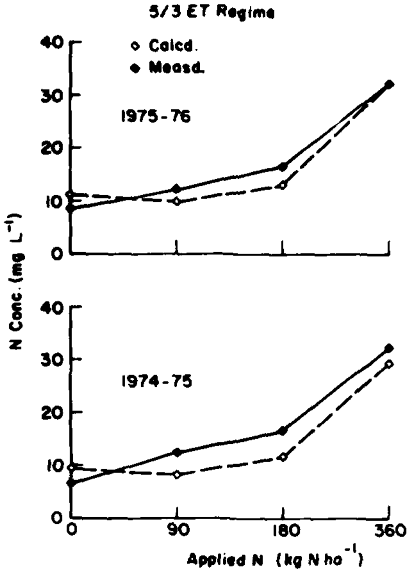

Figure 13. A comparison between measured and computed values of NO_3^- concentration as a function of applied N for the $^5/_3$ ET treatment.

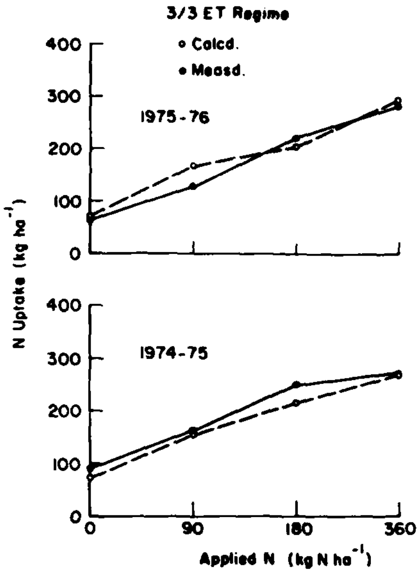

Figure 14. A comparison between measured and computed values of N uptake as a function of applied N for the $^3/_3$ ET treatment.

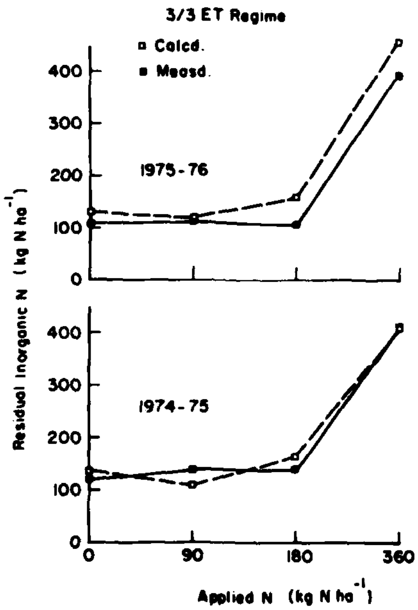

Figure 15. A comparison between measured and computed values of residual inorganic N as a function of applied N for the $^3/_3$ ET treatment.

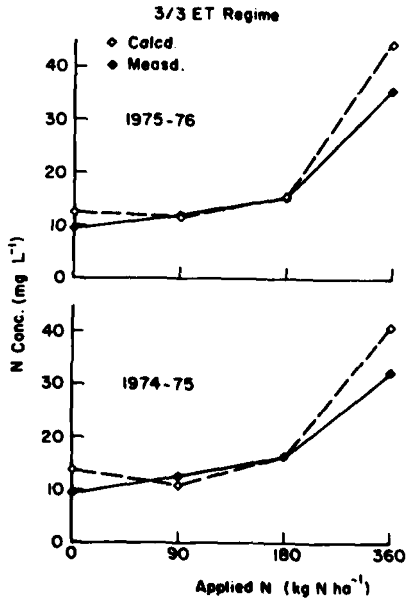

Figure 16. A comparison between measured and computed values of NO_3^- concentration as a function of applied N for for the $^3/_3$ ET treatment.

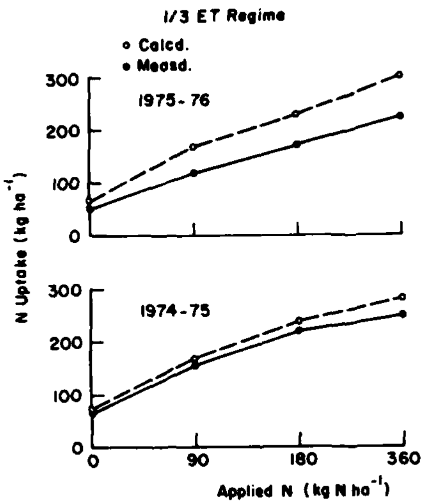

Figure 17. A comparison between measured and computed values of N uptake as a function of applied N for the $^{1}/_{3}$ ET treatment.

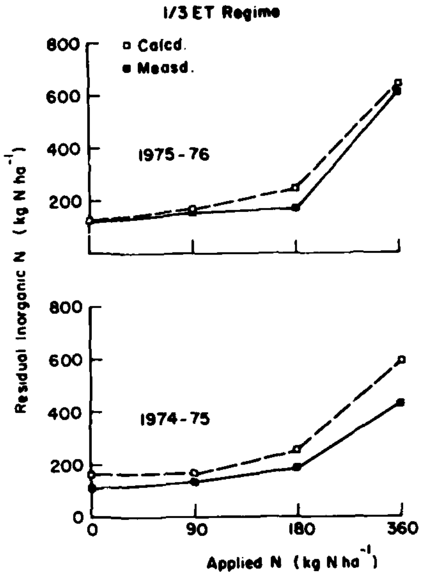

Figure 18. A comparison between measured and computed values of residual inorganic N as a function of applied N for the $^{1}/_{3}$ ET treatment.

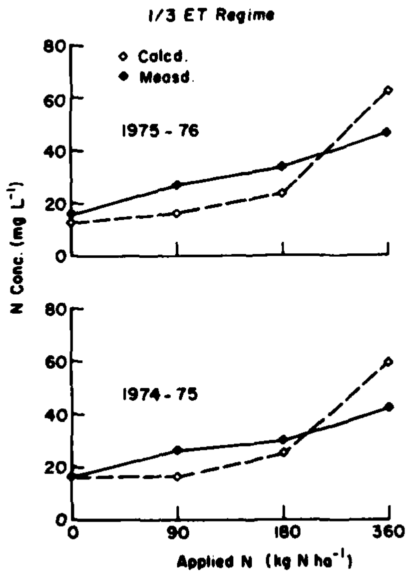

Figure 19. A comparison between measured and computed values of NO_3^- concentration as a function of applied N for the $^{1}/_{3}$ ET treatment.

ROLE OF COMPARTMENTAL MODELS FOR PLANNERS AND MANAGERS

The precision of the results obtained from a compartmental model is a function of the quality of available data and the level of aggregation of compartments and fluxes. As the level of aggregation increases, the precision decreases (National Research Council 1978), and of course the choice of that level depends on the kinds of questions that are being asked by the modeler. With proper selection of time increment and size of pools and fluxes giving rise to a meaningful averaging of events over time and space, compartmental models can be as precise as dynamic simulation models. The use of finely tuned dynamic models for management purposes may introduce difficulties as a result of 1) insufficient information regarding the processes and their interrelationships, 2) problems in obtaining required input data, 3) high cost of model application, and 4) knowledge of numerical analysis and sophisticated solution techniques. On the other hand, compartmental models, according to Levins (1966), sacrifice realism for the sake of generality.

Verification of the compartmental model by the two case studies presented in this chapter as well as those

models cited in the literature (see *Existing Models*) illustrate the potential capabilities of compartmental models in predicting the behavior of N in soil-water-plant systems under artificial as well as natural stresses. The uncertainties that exist in measuring some of the pools and fluxes of N as well as the rates of transformation impose limitations on the use of the models (Kohl et al. 1978, National Research Council 1978). The fact that these limitations should be evaluated for the particular conditions for which the models are used emphasizes the importance of team efforts in applying the models. It is the cooperation of modelers, researchers and decision-makers that sets the stage for a continuous feedback from and input to the model so that the model can be improved. In other words, the model must be considered dynamic in nature, as in a real system, to provide a forum for future revisions and modifications, and hopefully increased utility.

LITERATURE CITED

Aldrich, S.R. (1972) Some effects of crop production technology on environmental quality. *Biological Science*, vol. 22, no. 1, p. 90-95.

Allison, F.E. (1955) The enigma of soil nitrogen balance sheets. In *Advances in Agronomy* (A.G. Norman, Ed.). New York: Academic Press, vol. 7, p. 213-250.

Allison, F.E. (1965) Evaluation of incoming and outgoing processes that affect soil nitrogen. In *Soil Nitrogen* (W.V. Bartholomew and F.E. Clark, Ed.). Madison, Wisc.: American Society of Agronomy, vol. 10, p. 578-606.

Ayers, R.S. and R.L. Branson (Eds.) (1973) Nitrates in the Upper Santa Ana River Basin in relation to groundwater pollution. California Agricultural Experiment Station Bulletin 861.

Biggar, J.W., D.R. Nielsen, K.K. Tanji and J. MacIntyre (1974) Field investigation of water and nitrogen movement in Yolo soil. In *Nitrates in Effluents from Irrigated Lands*, Annual Report to NSF, Grant No. G134733X, University of California, Davis, p. 28-47.

Boawn, L.C., C.E. Nelson, F.G. Viets and C.L. Crawford (1960) Nitrogen carrier and nitrogen rate influence on soil properties and nutrient uptake by crops. Washington Agricultural Experiment Station Bulletin 614, p. 1-24.

Bouwer, H. (1974) Design and operation of land treatment systems for minimum contamination of groundwater. *Ground Water*, vol. 12, no. 3, p. 140-147.

Broadbent, F.E. (1976) Field trials with isotopes, Davis site. In *Nitrate in Effluents from Irrigated Lands*. Annual Report to NSF, Grant No. AEN 74-11136A01, University of California, Davis, p. 15-29.

Commoner, B. (1970) Threats to the integrity of the nitrogen cycle: Nitrogen compounds in soil, water, atmosphere and precipitation. In *The Changing Global Environment* (S.F. Singer, Ed.). Boston: D. Reidel Publishing Company, p. 341-366.

Crutzen, P.J. (1972) SST'S a threat to the earth's ozone shield. *Ambio*, vol. 3, p. 201-210.

Delwich, C.C. (1970) The nitrogen cycle. *Scientific American*, vol. 223, no. 3, p. 137-146.

Dryden, F.D. and C. Chen (1978) Groundwater recharge with reclaimed waters from the Pomona, San Jose Creek, and Whittier Narrows plants. In *State of Knowledge in Land Treatment of Wastewater*. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory, vol. 1, p. 241-251.

Duffy, J., C. Chung, C. Boast and M. Franklin (1975) A simulation model of biophysicochemical transformations of nitrogen in tile-drained corn belt soil. *Journal of Environmental Quality*, vol. 4, p. 477-486.

Endelman, F.J., M.L. Northrup, D.R. Keeney, J.R. Boyle and R.R. Hughes (1972) A systems approach to an analysis of the terrestrial nitrogen cycle. *Environmental Systems*, vol. 2, p. 3-19.

Erickson, E. (1959) Swedish atmospheric chemistry. *Svensk Kem. Tidskr.*, vol. 71, p. 15-32.

Fried, M., K.K. Tanji and R.M. Van De Pol (1976) Simplified long-term concept for evaluating leaching of nitrogen from agricultural land. *Journal of Environmental Quality*, vol. 5, p. 197-200.

Gordon, G. (1969) *System Simulation*. Englewood Cliffs, N.J.: Prentice-Hall.

Hutchinson, G.E. (1954) The biochemistry of the terrestrial atmosphere. In *The Earth as a Planet* (G.P. Kuiper, Ed.) Chicago: University of Chicago Press, p. 371-433.

Iskandar, I.K., R.S. Sletten, D.C. Leggett and T.F. Jenkins (1976) Wastewater renovation by a prototype slow infiltration land treatment system. CRREL Report 76-19. AD A029744.

Iskandar, I.K., R. Bates, S. Quarry, F. Page and J. Ingersoll (In prep.) Changes in soil characteristics and climatology during five years of wastewater application to CRREL test cells. CRREL Special Report.

Jenkins, T.F., A.J. Palazzo, P.W. Schumacher, D.B. Keller, J.M. Graham, S.T. Quarry, H.E. Hare, J.J. Bayer, Jr. and E.S. Foley (1978) Five-year performance of CRREL land treatment test cells; water quality plant yields and nutrient uptake. CRREL Special Report 78-26. ADA-086 172.

Jenkins, T.F., A.J. Palazzo, P.W. Schumacher, W.E. Hare, P.L. Butler, C.J. Diener and J.M. Graham (1981) Seven-year performance of CRREL slow-rate land treatment prototypes. CRREL Special Report 81-12.

Kardos, L.T. and W.E. Sopper (1974) Renovation of municipal wastewater through land disposal by spray irrigation. In *Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland* (E.W. Sopper and L.T. Kardos, Eds.). Water Pollution Control Technology Series, Report No. EPA-660/2-74-003, Washington, D.C.: Environmental Protection Agency, p. 131-145.

Kohl, D.H., G. Shearer and F. Vithayanthil (1978) Mass balance studies. 1. Critique of "Nitrogen inputs and outputs: A valley basin study." In *Nitrogen in the Environment* (D.R. Nielsen and J.G. MacDonald, Eds.). New York: Academic Press, vol. 1, p. 183-200.

Levins, R. (1966) The strategy of model building in population biology. *American Scientist*, vol. 54, no. 4, p. 421-431.

Mehran, M. and K.K. Tanji (1974) Computer modeling of nitrogen transformations in soils. *Journal of Environmental Quality*, vol. 3, p. 391-396.

Miller, R.J. and R.B. Smith (1976) Nitrogen balance in the Southern San Joaquin Valley. *Journal of Environmental Quality*, vol. 5, p. 274-278.

National Research Council (1970) Nutrient requirements of beef cattle. National Academy of Sciences, Washington, D.C., no. 4, 4th revised edition.

National Research Council (1978) Nitrates: An environmental

assessment. National Academy of Sciences, Washington, D.C.

Olson, R.A. (1978) The indispensible role of nitrogen in agricultural production. In *National Conference on Management of Nitrogen in Irrigated Agriculture* (P.F. Pratt, Ed.). p. 1-31.

Owens, L.D. (1960) Nitrogen movement and transformations in soils as evaluated by a lysimeter study utilizing isotopic nitrogen. *Soil Science Society of America Proceedings*, vol. 24, p. 372-376.

Palazzo, A.J. and T.F. Jenkins (1979) Land application of wastewater: Effect on soil and plant potassium. *Journal of Environmental Quality*, vol. 8, p. 309-312.

Potash Institute of America (1973) Plant food utilization. Atlanta, Georgia.

Sanai, M. and J. Shayegan (1978) Water pollution control through land disposal of secondary treated wastewater effluents. In *State of Knowledge in Land Treatment of Wastewater.* Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory, vol. 1, p. 231-238.

Schultz, A.D. (1969) A study of an ecosystem: The arctic tundra. In *The Ecosystem Concept in Natural Resource Management* (G.M. Van Dyne, Ed.). New York: Academic Press, p. 77-93.

Söderlund, R. and G.H. Svensson (1976) The global nitrogen cycle. In *Nitrogen, Phosphorus and Sulfur–Global Cycles.* (G.H. Svensson and R. Söderlund, Eds.). Stockholm, p. 23-73.

Tanji, K.K. (1976) A conceptual hydrosalinity model for predicting salt load in irrigation return flows. *Proceedings of the International Salinity Conference*, Texas Technical University, Lubbock, Texas, p. 49-70.

Tanji, K.K., M. Fried and R.M. Van De Pol (1977) A steady-state conceptual model for estimating nitrogen emissions from cropped lands. *Journal of Environmental Quality*, vol. 6, p. 155-159.

Tanji, K.K., F.E. Broadbent, M. Mehran and M. Fried (1979) An extended version of a conceptual model for evaluating annual nitrogen leaching losses from croplands. *Journal of Environmental Quality*, vol. 8, p. 114-120.

Tyler, K.B. and F.E. Broadbent (1958) Nitrogen uptake by ryegrass from three tagged ammonium fertilizers. *Soil Science Society of America Proceedings*, vol. 22, p. 231-234.

Van Dyne, G.M. (1970) A systems approach to grasslands. *Proceedings XI International Grassland Congress.* University of Queensland Press, p. A131-A143.

APPENDIX A: DESCRIPTION AND PROGRAM LISTING OF THE COMPARTMENTAL NITROGEN MODEL

The program for the compartmental model consists of only one main program. All input data are given in free format. The units for all N and water values are in kg ha^{-1} yr^{-1} and cm yr^{-1}, respectively. Input data are as follows:

Record (1):
EPAN = Pan evaporation (growing season), cm
EPANP = Pan evaporation (nongrowing season), cm
KP = potential ET coefficient for grass
B = fallow soil ET coefficient

Record (2):
YMAX = maximum uptake of N
XMIN = minimum applied N for which uptake is zero
KM = constant for curvature of the uptake vs applied N

Record (3):
EIAE = irrigation application efficiency
A = precipitation runoff coefficient
F = deep percolation coefficient

Record (4):
NISN = resident inorganic soil N

Record (5):
CIW = N concentration in irrigation water
CP = N concentration in precipitation

Record (6):
G = gas loss coefficient for inorganic N
NAOF = applied organic N
D = gas loss coefficient for organic N
KM1 = mineralization rate for applied organic N
NMCF = N conversion factor

Record (7):
NFN = amount of N fixed
KM2 = mineralization rate for fixed N

Record (8):
C = denitrification coefficient
KM3 = mineralization rate for resident soil organic N

Record (9):
NCELL = cell number
NY = period of growth
QIW = amount of applied wastewater
QP = amount of precipitation
QPER = amount of water percolated
NAIF = applied inorganic N at the soil surface
NOSN = resident organic soil N

APPENDIX B: A TRANSIENT COMPARTMENTAL MODEL FOR PREDICTION OF NITRATE LEACHING LOSSES AND NITROGEN UPTAKE BY GRASS IN SLOW INFILTRATION SYSTEMS OF LAND APPLICATION OF WASTEWATER

```
C**
C**    DEFINITION OF INPUT VARIABLES :
C**    QIW = IRRIGATION WATER
C**    EIAE = IRRIGATION APPLICATION EFFICIENCY
C**    QP = PRECIPITATION
C**    A = PRECIPITATION RUNOFF COEFFICIENT
C**    EPAN = PAN EVAPORATION FOR GROWING SEASON
C**    EPANP = PAN EVAPORATION FOR NONGROWING SEASON
C**    KP = POTENTIAL ET COEFFICIENT FOR GRASS DURING
C**         GROWING SEASON
C**    KPP = POTENTIAL ET COEFFICIENT FOR GRASS DURING
C**          NONGROWING SEASON
C**    F = DEEP PERCOLATION COEFFICIENT
C**    E = CROP ET COEFFICIENT
C**    B = FALLOW ET COEFFICIENT
C**    N = NITROGEN
C**    CIW = N CONCENTRATION IN IRRIGATION WATER
C**    CIWRNP = N PICKUP CONC. BY IRRIGATION RUNOFF WATER
C**    CP = N CONC. IN PRECIPITATION
C**    CPRONP = N PICKUP CONC. BY PRECIPITATION RUNOFF WATER
C**    G = GAS LOSS COEFFICIENT FOR INORGANIC N FERTILIZER
C**    NAIF = APPLIED INORGANIC N FERTILIZER
C**    NAOF = APPLIED ORGANIC NITROGEN FERTILIZER
C**    D = GAS LOSS COEFFICIENT FOR ORGANIC N FERTILIZER
C**    KM1 & KM2 & KM3 = MINERALIZATION RATE CONSTANTS
C**    T = TIME
C**    NFN = FIXED N
C**    NOSN = RESIDENT ORGANIC SOIL N
C**    NISN = RESIDENT INORGANIC SOIL N
C**    C = LOSS COEFFICIENT FOR DENITRIFICATION
C**    H = HARVESTED CROP COEFFICIENT
C**
C**
C**
       REAL KP,KPP,NAIF,NAOF,KM1,NFN,KM2,NOSN,KM3,NISN,
      1NMCF,NEIW,NIWRO,NP,NEP,NPRO,NIFGL,NEAIF,NOFGL,
      2NEAOF,NRAOF,NAOFM,NRFN,NFNM,NRCSN,NOSNM,NRSN,
      3NIRZ,ND,NEIRZ,NHC,NFORZ,L,NRISN,NLL,NDP,NSDW,NSIRF
         CALL ATTDEV(6,8,2,66)
       NR = 5
       NW = 6
       CALL CONTRL(1,'INPUT',NR)
       CALL CONTRL(2,'OUTPUT',NW)
C**    HYDROLOGY SUBMODEL
C**
C**   INPUT DATA AND COEFFICIENTS FOR HYDROLOGY SUBMODEL
         READ(NR,*)EIAE,A,KP,KPP,F,E,B
         READ(NR,*)EPAN,EPANP
         READ(NR,*)QIW,QP
C**    COMPUTATION OF DEEP PERCOLATION AND SURFACE RUNOFF
       QEIW = EIAE * QIW
       QIWRO = (1.0-EIAE)* QIW
       QPRO = A * QP
       QEP = (1.0-A)* QP
       QSW = QEIW + QEP
       DPET = KP * EPAN
       DPETP = KPP * EPANP
       QET = E * DPET + B * DPETP
       QLL = QSW - QET
       QDP = F * QLL
       QSDW = (1.0-F) * QLL
       QSIRF = QIWRO + QPRO + QSDW
C**    NITROGEN SUBMODEL:
C**
```


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```
C**    INPUT DATA AND COEFFICIENTS FOR NITROGEN SUBMODEL
        READ(NR,*)CIW,CIWRNP,CP,CPRONP
        READ(NR,*)G,NAOF,D,KM1,T,NMCF
        READ(NR,*)NFN,KM2
        READ(NR,*)NAIF
        READ(NR,*)NOSN
        READ(NR,*)KM3
        READ(NR,*)NISN
        READ(NR,*)C,H
C**    COMPUTATION OF N SPECIES IN SOIL & SURFACE WATERS
C**    IRRIGATION WATER :
       NEIW = CIW * QEIW * NMCF
       CIWRO = CIW + CIWRNP
       NIWRO = CIWRO * QIWRO * NMCF
C**    PRECIPITATION :
       NP = CP * QP * NMCF
       NEP = CP * QEP * NMCF
       CPRO = CP + CPRONP
       NPRO = CPRO * QPRO * NMCF
C**    APPLIED INORGANIC N FERTILIZER :
       NIFGL = G * NAIF
       NEAIF = (1.0-G) * NAIF
C**    APPLIED ORGANIC N FERTILIZER :
       NOFGL = D * NAOF
       NEAOF = (1.0-D) * NAOF
       NRAOF = NEAOF * EXP(-KM1 * T)
       NAOFM = NEAOF - NRAOF
C**    FIXED NITROGEN :
       NRFN = NFN * EXP(-KM2 * T)
       NFNM = NFN - NRFN
C**    RESIDENT ORGANIC SOIL NITROGEN :
       NROSN = NOSN * EXP(-KM3 * T)
       NOSNM = NOSN - NROSN
C**    RESIDUAL ORGANIC SOIL N AFTER HARVEST :
       NRSN = NROSN + NRAOF + NRFN
C**    NITROGEN INFLOW TO ROOT ZONE :
       NIRZ = NEIW+NEP+NEAIF+NAOFM+NISN+NFNM+NOSNM
C**    DENITRIFICATION AND UNACCOUNTED LOSSES :
       ND = C * NIRZ
C**    EFFECTIVE N INFLOW TO ROOT ZONE :
       NEIRZ = NIRZ - ND
C**    HARVESTED CROP UPTAKE :
       NHC = H * NEIRZ
C**    RESIDUAL INORGANIC SOIL N AFTER HARVEST :
       NEORZ = NEIRZ - NHC
       L = QLL/(QEIW + QEP)
       NRISN = (1.0-L) * NEORZ
C**    LEACHING LOSSES FROM ROOT ZONE :
       NLL = L * NEORZ
       CLL = NLL/(QLL * NMCF)
C**    NITROGEN IN RETURN FLOWS :
       CDP = CLL
       CSDW = CLL
       NDP = CDP * QDP * NMCF
       NSDW = CSDW * QSDW * NMCF
       CSIRF = (CIWRO*QIWRO+CPRO*QPRO+CSDW*QSDW)/QSIRF
       NSIRF = CSIRF * QSIRF * NMCF
C**
C**
C**
       WRITE(NW,11)
 11    FORMAT(1H1,'INPUT DATA AND COEFFICIENTS FOR HYDROLOGY SUBMODEL'//)
       WRITE(NW,12)
 12    FORMAT(        '     QIW      EIAE      QP          A       EPAN      KP
      1     EPANP     KPP       F        E         B'//)
       WRITE(NW,13)QIW,EIAE,QP,A,EPAN,KP,EPANP,KPP,F,E,B
 13    FORMAT(2X,F7.2,3X,F4.2,4X,F5.1,5X,F4.2,3X,F7.2,4X,
      1F4.2,2X,F7.2,3X,F4.2,6X,F3.1,5X,F4.2,4X,F4.2//)
C**
       WRITE(NW,14)
 14     FORMAT(1H0,'INPUT DATA AND COEFFICIENTS FOR N SUBMODEL'//)
       WRITE(NW,15)
```

```
15    FORMAT(1H0'   G        NAIF       NAOF          D         KM1         T          NF
     1N         KM2        NOSN        KM3        NISN         C             H         NMCF'
     2/)
      WRITE(NW,16)G,NAIF,NAOF,D,KM1,T,NFN,KM2,NOSN,KM3,NISN,C,H,NMCF
 16   FORMAT(2X,F3.1,2X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2,3X,
     1F6.4,3X,F7.1,3X,F6.5,3X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2//)
      WRITE(NW,10)CIW
 10   FORMAT(1H0,20X,'N CONC. IN IRRIGATION WATER=',F7.2)
      WRITE(NW,9)CP
  9   FORMAT(1H0,20X,'N CONC. IN PRECIPITATION=',F7.2//)
C**
      WRITE(NW,17)
 17   FORMAT(1H1,'OUTPUT VARIABLES OF HYDROLOGY SUBMODEL'/)
      WRITE(NW,18)QEIW
 18   FORMAT(1H0,20X,'EFFECTIVE IRRIGATION WATER IN CM=',F7.
     12)
      WRITE(NW,19)QIWRO
 19   FORMAT(1H0,20X,'IRRIGATION WATER RUNOFF IN CM=',F7.2)
      WRITE(NW,20)QEP
 20   FORMAT(1H0,20X,'EFFECTIVE PRECIPITATION IN CM=',F7.2)
      WRITE(NW,21)QPRO
 21   FORMAT(1H0,20X,'PRECIPITATION RUNOFF IN CM=',F7.2)
      WRITE(NW,22)QSW
 22   FORMAT(1H0,20X,'SOIL WATER IN CM=',F7.2)
      WRITE(NW,23)QET
 23   FORMAT(1H0,20X,'EVAPOTRANSPIRATION IN CM=',F7.2)
      WRITE(NW,24)QLL
 24   FORMAT(1H0,20X,'LEACHING LOSSES IN CM=',F7.2)
      WRITE(NW,25)QDP
 25   FORMAT(1H0,20X,'DEEP PERCOLATION IN CM=',F7.2)
      WRITE(NW,26)QSDW
 26   FORMAT(1H0,20X,'SUBSURFACE DRAINAGE IN CM=',F7.2)
      WRITE(NW,27)QSIRF
 27   FORMAT(1H0,20X,'SURFACE RETURN FLOW IN CM=',F7.2//)
      WRITE(NW,30)
 30   FORMAT(1H0,'OUTPUT VARIABLES OF N SUBMODEL'//)
      WRITE(NW,31)
 31   FORMAT(1H0,5X,'IRRIGATION WATER :'/)
      WRITE(NW,32)NEIW
 32   FORMAT(1H0,20X,'N MASS FROM EFFECTIVE IRRIGATION WATER=',F7.2)
      WRITE(NW,33)NWRO
 33   FORMAT(1H0,20X,'N MASS FROM RUNOFF WATER=',F7.2)
C**
      WRITE(NW,36)
 36   FORMAT(1H0,5X,'PRECIPITATION :'/)
      WRITE(NW,37)NEP
 37   FORMAT(1H0,20X,'N MASS FROM EFFECTIVE PRECIPITATION=',F7.2)
      WRITE(NW,38)NPRO
 38   FORMAT(1H0,20X,'N MASS IN PRECIPITATION RUNOFF=',F7.2)
      WRITE(NW,41)
 41   FORMAT(1H0,5X,'APPLIED INORGANIC & ORGANIC FERTILIZER :'/)
      WRITE(NW,42)NEAIF
 42   FORMAT(1H0,20X,'EFFECTIVE APPLIED INORGANIC  NITROGEN FERTILIZER
     1='F7.2)
      WRITE(NW,43)NEAOF
 43   FORMAT(1H0,20X,'EFFECTIVE APPLIED ORGANIC N FERTILIZER=',F7.2)
      WRITE(NW,44)NAOFM
 44   FORMAT(1H0,20X,'APPLIED ORGANIC N FERTILIZER MINERALIZED=',F7.2)
      WRITE(NW,45)NRISN
 45   FORMAT(1H0,20X,'RESIDUAL INORGANIC N AFTER HARVEST=',F7.2)
      WRITE(NW,46)
 46   FORMAT(1H0,5X,'FIXED N ; RESIDENT ORGANIC SOIL N ;RESIDUAL ORGANIC
     1 SOIL N AFTER HARVEST'/)
      WRITE(NW,47)NFNM
 47   FORMAT(1H0,20X,'FIXED N MINERALIZED=',F7.2)
      WRITE(NW,48)NOSNM
 48   FORMAT(1H0,20X,'RESIDENT ORGANIC SOIL N MINERALIZED=',
     1F7.2)
      WRITE(NW,49)NRSN
 49   FORMAT(1H0,20X,'RESIDUAL ORGANIC SOIL N AFTER HARVEST=',F8.1)
      WRITE(NW,50)
```

```
50    FORMAT(1H0,5X,'DENITRIFICATION & UNACCOUNTED LOSSES:'/)
      WRITE(NW,51)ND
51    FORMAT(1H0,20X,'DENITRIFICATION & OTHER LOSSES=',F7.2)
      WRITE(NW,53)
53    FORMAT(1H0,5X,'EFFECTIVE INFLOW TO ROOT ZONE ; HARVESTED CROP UPTA
     1KE:'/)
      WRITE(NW,52)NIRZ
 52   FORMAT(1H0,20X,'MINERALIZED N INPUT TO ROOT ZONE=',F7.2)
      WRITE(NW,54)NEIRZ
54    FORMAT(1H0,20X,'EFFECTIVE N INFLOW TO ROOT ZONE=',F7.2
     1)
      WRITE(NW,55)NHC
55    FORMAT(1H0,20X,'HARVESTED CROP UPTAKE=',F7.2)
      WRITE(NW,56)
56    FORMAT(1H0,5X,'LEACHING LOSSES FROM ROOT ZONE:'/)
      WRITE(NW,57)NLL
57    FORMAT(1H0,20X,'N LEACHING LOSSES=',F7.2)
      WRITE(NW,58)CLL
58    FORMAT(1H0,20X,'N CONC. IN LEACHATE,MG N/L=',F7.2)
      WRITE(NW,60)
60    FORMAT(1H0,5X,'N IN RETURN FLOWS:'/)
      WRITE(NW,61)NDP
61    FORMAT(1H0,20X,'MASS EMISSION THRU. DEEP PERCOLATION='
     1,F7.2)
      WRITE(NW,62)NSDW
62    FORMAT(1H0,20X,'MASS EMISSION THRU. COLLECTED SUBSURFACE DRAINAGE=
     1',F7.2)
      WRITE(NW,63)NSIRF
63    FORMAT(1H0,20X,'MASS EMISSION THRU. SURFACE IRRIGATION RETURN FLOW
     1=',F7.2)
      WRITE(NW,64)CSIRF
64    FORMAT(1H0,20X,'N CONC. IN SURFACE IRRIGATION RETURN FLOW=',F7.2)
      CALL CONTRL(4,'INPUT',NR)
      CALL CONTRL(4,'OUTPUT',NW)
      CALL EXIT
      END
```

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Bibliography: p. 16.
1. Land treatment. 2. Leaching. 3. Models. 4. Nitrogen. 5. Soils. 6. Waste treatment. I. Tanji, K.K. II. Iskandar, I.K. III. United States. Army. Corps of Engineers. IV. Army Cold Regions Research and Engineering Laboratory. V. Series: CRREL Report 81-23.

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